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Ballistic impact experiments and modelling of sandwich armor for numerical simulations

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Abstract

In this paper some experimental results of a bullet impact on composite armor are discussed together with numerical modeling approaches. The development of high-quality composite sandwiches for ballistic protection is the target of a grant project in terms of which the research is being conducted. Traditionally, a vehicle ballistic protection is mainly achieved using metal-based armor which is heavy and thus negatively affects other vehicle parameters, such as maneuverability. These days, composite or hybrid sandwiches are becoming more and more popular. Numerical simulations allow for a reduction of the number and variability of experiments needed to obtain appropriate design of ballistic protection, but they require verified modeling approaches and reliable material data. Therefore, different modelling approaches have been tested and possibilities to adjust these models to experimental data were investigated.

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Keywords: bullet impact; numerical simulations; ballistic protection; composite sandwich armor;

1. Introduction

Experimental methods play an essential role in developing new designs or materials, but their applications are demanding in terms of time, cost and realization. Due to the development of knowledge in the field of phenomenological material models and methods themselves, especially numerical analysis methods of mechanical systems, the design process and structure analysis is commonly supported by their usage. As far as conventional construction is concerned, numerical analysis is used routinely in cases when it is necessary to assess the stiffness, durability, frequency characteristics, etc. But also for example in the analysis of breakdown situations or structures that perform their functions through a partial or total destruction, as in our case, the development of ballistic shields protection. It is desirable to carry out experiments and numerical simulations together. We expect a deepening understanding of experiments due to numerical simulations and also a continuous consequent promotion of rationally designed experiments, thus reducing their number.

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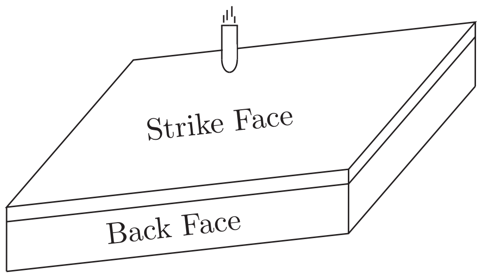

Fig. 1. A model of a sandwich armor section. The projectile first hits the layer called "strike face" which is made of armor, and then enters the composite layer called "back face".

Currently there is no unified theory that would cover the response of materials under impact loading for a wide range of impact velocity and different projectile mass and geometry. Our focus will be primarily on the damage of steel armor which is often used as one of the elements of sandwich armor called "strike face" – see Figure 1. The main function of this layer is to absorb the kinetic energy of a bullet, its destabilization, deflection, and deformation. The strike face is made of a very hard armor or ceramics. The next layer is called a "back face" and its function is to absorb the remaining kinetic energy of the deformed and/or fragmented projectile. Hence, this layer must be resilient, yet strong enough to prevent the projectile penetration. To reduce the weight of the ballistic protection, a composite fabric of different materials (Aramid, Polyolefin, Ultra-high-molecular-weight polyethylene) was chosen as a back face. The resulting sandwich will consist of yet another layer – usually a part of a protected structure, but for the purpose of a ballistic resistance these two layers are particularly crucial and therefore from now on we will only consider these two.

In ballistic impact simulations structural models based on finite element method as well as analytical models need significant simplifications and their correctness is strongly dependent on modelling approach. The proper choice of a computational procedure and material model – especially damage criteria depends mainly on the geometry of the interacting objects, impact velocity, the kind of materials, but also on the boundary conditions of the target etc. Therefore, the execution of the experiments with a simple geometry is crucial for its subsequent numerical simulation during which the comparison of deformation modes and the overall process of experiment with simulations lead to the choice of appropriate damage criteria and adjusting their parameters. Hence ballistic experiments with armor plates with different impact velocities and combination of armor and composite plates have been carried out.

The simulation of a sandwich composite penetration is a complex task involving an interaction of three main objects with each other: the bullet, the "strike face", and the "back face". For this reason, the numerical simulations of the bullet impact performance on a composite sandwich were divided into three steps. The steel ball impact through the composite plate, the real bullet impact into the steel "strike face", and then the impact of a composite sandwich with a real bullet. For the initial calculations of the composite sandwich impact, a geometrically simple case was chosen: a projectile impact on a composite plate. This case is described in [4] in which all necessary material data are also provided, along with the experiment results. The results of this calculation depending on the chosen failure model and its parameters have been published in [8]. This paper presents our progress with the "strike face" simulation and extends the obtained experimental data.

2. Strike face impact experiments

For the simulation purposes, armor plate impacts with real bullet firing tests were conducted. In our case, the armor was ARMOX 500T by the Swedish company SSAB AB with a thickness of 3.5 mm, yield stress $R_{p0.2}$ = 1 414 MPa, and tensile strength R_m = 1 650 MPa. The armor plate was mounted along the edges into the frame of the impact rest as shown in Figure 2. The ammo was .223 Remington, the bullet weight of 3.6 g designation FMJ (M193). The shooting was performed using a firing rest at the distance of 15 m. The impact velocity was measured by a radar located at the firing rest and also using optical gates placed before the target. The residual velocity was measured by a high-speed camera in the area behind the target and subsequently determined by an analysis of consecutive frames of


Fig. 2. The impact rest with the armor plate "strike face" and the woven composite plate "back face".

the projectile or its fragments. The error of measurement was determined by experimenters to ±10 m/s. The measured values are shown in Table 1. The change of the impact velocity of the projectile was obtained by modifying the weight and type of the gunpowder in cartridges.

Table 1. The measured residual and impact velocity of the projectile impact at the armor plate.

Impact velocity (*m/s*)	809	841	878	910	942	975	1 033
Residual velocity (*m/s*)	448	658	712	696	674	784	836

3. Composite sandwich impact experiments

Experimental shooting tests of the "strike face" armor plate were followed by a shooting into a composite sandwich as shown in Figure 1. A composite plate woven sequentially of three different materials was added behind the armor plate with a thickness of 3.5 mm. The area density of this plate was approximately the same for all materials. After the initial comparative shooting tests, the following three materials were selected for further testing:

- Aramid woven fabric in phenol matrix (mass fraction of matrix 12%)
- Polyolefin woven fabric in phenol matrix (mass fraction of matrix 20%)
- Ultra-high-molecular-weight polyethylene (denoted as UHMWPE) woven fabric in phenol matrix (mass fraction of matrix 20%)

The shooting results showed that only the sandwich armor composed of aramid fibers could capture the projectile so as to prevent perforation – Table 2. The perforation occurred in four out of six shots. The aramid fiber samples exhibited the largest permanent deformation during the tests.The significant degree of deformation together with the overall strength of aramid fibers are two reasons why, in accordance with the observed results, the material can catch projectiles. In particular, the zone around the impact of bullets was many times higher than in the other material samples. It was the main reason for the great difference between the first and the second shot on the same sample. Only in one case did the first shot perforate the sandwich and the second bullet was captured by the armor. This was caused by the impact location of the first shot, relatively close to the edge of the sample as well as to the place of attachment, not allowing the material to deform sufficiently enough and absorb the energy of the shot.

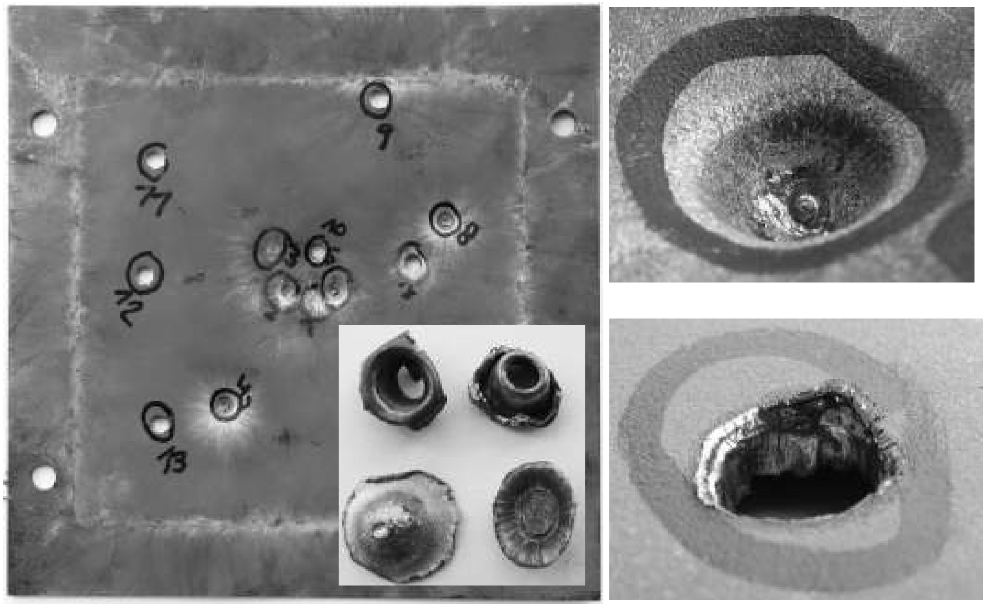

Fig. 3. The armor plate after thirteen rounds of testing, together with fragments of the used munition at lower impact velocities (left). Deformation of the armor plate (impact side) after the impact of the projectile at low velocity v_i = 793 m/s (top), and after the impact of a projectile at high velocity v_i = 1 050 m/s (bottom).

Table 2. Aramid

Impact velocity (*m/s*)	1004	999	988	992	984	985
Residual velocity (*m/s*)	0	432	458	512	315	0
First or second shot into specimen	first	second	first	second	first	second

A polyolefin composite sandwich was tested using the total of eight bullets and all of them perforated the armor – Table 3. The last two shots were carried out on a sample cured at a lower temperature than the others. This change of the technological process was performed in order to investigate the possibility of affecting mechanical properties of the fibers in relation to the curing temperature – however, this has not been proven.

Table 3. Polyolefin (N – normal temperature; LT – lower temperature)

Impact velocity (*m/s*)	986	996	987	982	984	989	992	989
Residual velocity (*m/s*)	451	606	558	581	560	615	535	492
Curing process conditions	N	N	N	N	N	N	LT	LT

The last set of the tested sandwich armor samples were composed of armor and a composite fabric made of ultra-high-molecular-weight polyethylene. The shootings results are presented in Table 4. This material is widely used for ballistic protection, but the results of our experiments did not prove its suitability. Therefore, modifications of the curing technological process were made, by lowering the curing temperature (denoted as LT), but also by the combination of lowering temperature and increasing pressure during the curing process (denoted as HPLT). The results indicate that these modifications have no significant effect on the material ability to absorb kinetic energy of the projectile.

Table 4. UHMWPE (N – normal temperature; LT – lower temperature; HPLT – higher pressure and lower temperature)

Impact velocity (*m/s*)	991	979	993	982	978	986	993	980	981	990	995
Residual velocity (*m/s*)	622	563	559	596	626	570	539	649	589	644	615
Toughening conditions	N	N	N	N	N	N	LT	LT	LT	HPLT	HPLT

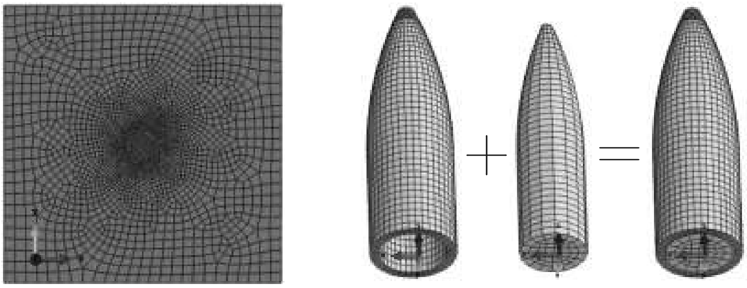

Fig. 4. The jacket, the core and the final projectile model created by merging them together.

4. Numerical simulations

It was necessary to create models of the bullet and the armored target in order to simulate a bullet impact on the strike face with real ammo. The bullet consisted of a tombak-plated steel jacket ($CuZn_{10}$) and a core which was made of lead and antimony alloy (Pb-Sb, yield stress 20 MPa, linear isotropic hardening). The jacket was modeled using 8 652 linear hexahedron elements (C3D8R) with elastic-plastic material behavior. To avoid a large distortion of the elements, ductile and shear failure was considered which led to the deletion of the element during the simulation and prevented its premature end (detailed jacket material data and damage parameters can be found in [4]). This, however, caused a loss of the projectile mass. This phenomenon could be avoided by using a Smooth Particle Hydrodynamics (SPH) formulation. Therefore the core was also described with 1 728 linear hexahedron elements (C3D8R) which were converted to SPH elements (PC3D) at the beginning of the simulation. They allow for very large deformations and their qualitative description of the core behavior at the impact of the projectile using elastic-plastic material model corresponds to the behavior of the projectile core captured by a high-speed camera – Figure 5. This bullet impact with the initial velocity $v_i = 1022\ m/s$ is also described by stress (von Mises) and equivalent plastic stain contours obtained from a numerical simulation at different moments – figure 7.

Table 5. Main material parameters used for numerical simulation.

	Armor	Bullet Core	Bullet Jacket
Density (kg/m^3)	7 875	11 000	7 800
Young's modulus (*MPa*)	210 000	24 150	210 000
Poisson's ratio	0.3	0.42	0.3

The armor plate was modeled using 38 101 linear hexahedron elements (C3D8R) with elastic-plastic material behavior described by the Johnson-Coock model (material parameters: A = 1 343 MPa, B = 7 487 MPa and n = 1.174 according to [5]) and the plate was fixed around the edges. The model parameters were derived from the armor material sheet supplied by the manufacturer. To allow armor penetration by the projectile, a failure model was also included. The description of the failure model by Johnson-Coock follows.

$$\bar{\varepsilon}_f^{pl} = \left[d_1 + d_2 \exp\left(d_3 \frac{p}{q}\right)\right]\left[1 + d_4 \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right]\left(1 + d_5 \hat{\theta}\right) \tag{1}$$

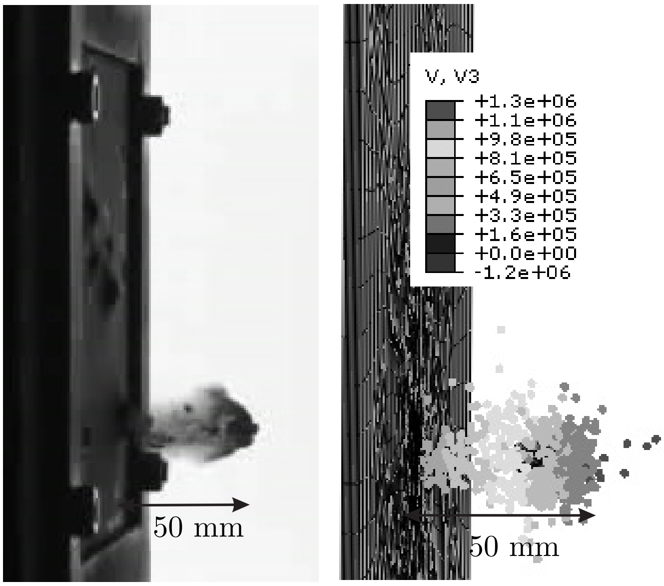

Fig. 5. The situation 50 microseconds after the impact (experiment on the left – impact velocity v_i = 1033 m/s, simulation on the right – impact velocity v_i = 1022 m/s.)

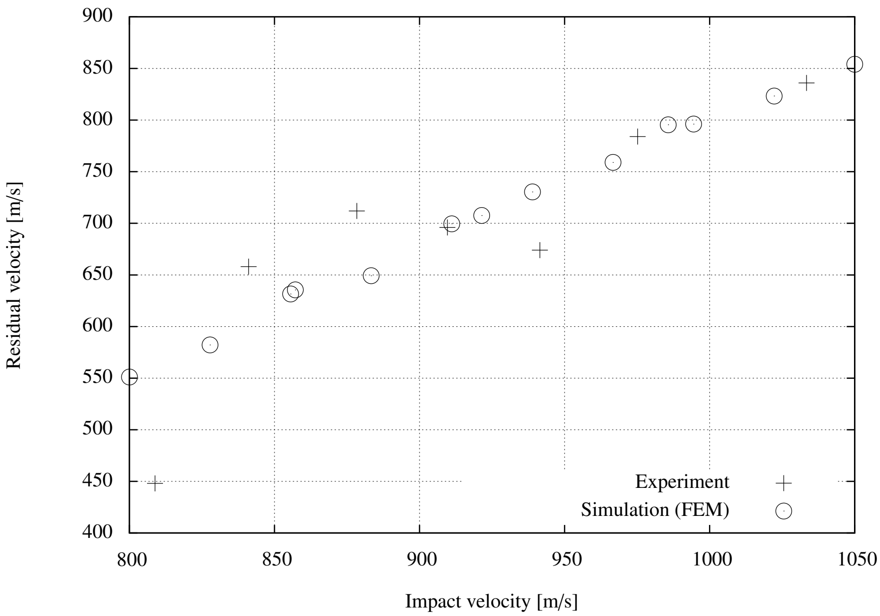

Fig. 6. The impact and residual velocity comparison of the experiment and numerical simulation results.

where d_1 to d_5 are the damage model parameters, $\dot{\varepsilon}_0$ is a reference strain rate, p is the pressure stress, q is the von Mises stress, $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate, $\bar{\varepsilon}_f^{pl}$ is the equivalent plastic strain at the onset of damage, and $\hat{\theta}$ is the non dimensional temperature. In our case, we neglected the dependence of damage on triaxiality (parameters d_2 and d_3) and the temperature dependence (parameter d_5). There are two remaining parameters. Parameter d_1 describes

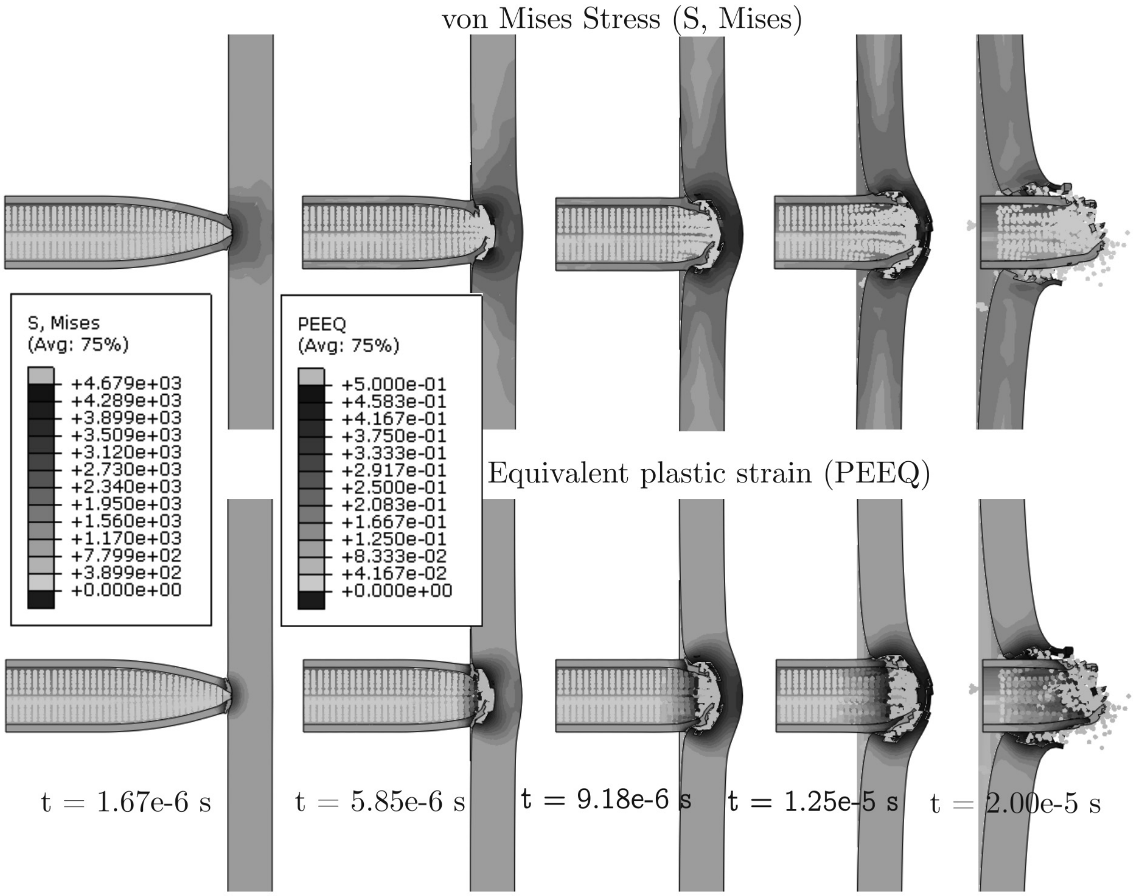

Fig. 7. Stress [MPa] (top) and Equivalent plastic strain [-] (bottom) presented in five different moments during the simulation of a bullet impact with the initial velocity $v_i = 1022\ m/s$.

the size of the equivalent plastic strain at the beginning of the failure and parameter d_4 adds impact damage depending on the strain rate. These two parameters were fitted to agree with the experiments.

The above-described mesh used for numerical simulations was the result of a compromise between accuracy and the computational time – the impact simulation was computed approximately a hundred times to fit the parameters. Also using SPH elements led to a rapid increase in computing time. Our aim was to create approximately equally sized elements that come into contact with each other after removing the projectile tip which was deleted as a result of material damage.

Thanks to the measured experimental values of residual velocities for different impact velocities, it was possible to find values for a pair of Johnson-Cook's parameters d_1 and d_4. In order to achieve this, the parametric study function in the software Abaqus/Explicit was used. The output of this implementation was several pairs of parameters which generated residual velocity for the given bullet input velocity v_i = 1 000 m/s, corresponding with the experimental tests. Once these two parameters were found, a parametric study was employed again, but there was a change in impact velocities v_i, and the residual velocities v_r were compared with the experiments. The best agreement was achieved with parameters d_1 = 0.25 and d_4 = 0.024 as shown in Figure 6.

5. Conclusions

Experimental firing tests with real ammunition to an armor plate “strike face” at various impact velocities of the projectile were conducted, together with simulations of this situation. After finding the parameters of the damage model, the results of the simulation showed a good agreement with the experimental data. This model is ready for a simulation of an impact sandwich armor which will be carried out after determining necessary mechanical properties of the aramid composite “back face” material to support the development of elements for vehicle ballistic protection.

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